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Abstract. The advantages of using of table top x-ray lasers (XRLs) for different applications have been described. Examples of the first successful use of XRLs, the current efforts in applying them and the potential applications where an XRL can be used in future have been discussed. Modeling results showing the possibility of 3-4 times shorter wavelength capillary discharge x-ray lasers and calculated spectrum of Xe capillary EUV source are presented.

INTRODUCTION

The high efficiency of short pulse duration transient and electric current-driven capillary discharge x-ray lasers have allowed the scaling of these lasers to table-top dimensions. This achievement has opened new possibilities for many different applications. We discuss some past, present and future applications using table-top x-ray lasers.

The applications require more efficient and powerful x-ray lasers with shorter wavelengths and in some cases shorter pulse durations. Specifically, in this paper, we summarize nowadays achievable applications, such as shadowgraphy, soft-x-ray imaging, x-ray and photoelectron spectroscopy and some others. The interferometry and study of XRL interactions with matter will be treated in detail.

In the last part of the paper we present the gain calculations for capillary discharges driven by large, up to 300 kA currents which allow to achieve shorter wavelengths and hence enable new applications. We also discuss EUV sources based on capillary discharge for such an important application as microlithography.

TABLE-TOP X-RAY LASERS AND APPLICATIONS

During the last decade there was substantial progress in scaling down x-ray lasers in dimensions, pumping energy, and cost. XRLs have achieved improved characteristics of peak power, efficiency, coherence, higher repetition rates of operation and dramatically decreased pulse duration. But the major goal of scaling to affordable, table-top dimensions during the last decade was driven by the need to utilize these unique x-ray sources for a spectrum of new potential applications and, therefore, substantially increase the range of experimental tools available to a larger user base. Another path is the usage of a large, central, multi-user facilities, utilizing accelerator-based ASE x-ray laser sources which have simultaneously many record parameters, e.g. brightness, tunability and short pulse duration, but at a substantially higher cost and size. In some respects, these resemble the past of plasma x-ray lasers when they were using large, expensive, high power laser facilities. Table 1 compares current plasma-based table top XRL parameters with one of the future DESY VUV- Free Electron Laser (FEL) sources planned to become operational in the next few years. Many achieved parameters of plasma-based x-ray lasers heated by powerful lasers and electrical discharges compare favorably to large scale present and near future particle acceleration x-ray sources. Definitely, plasma XRLs will continue to improve during the next years with the potential to approach the characteristics of FELs. In some cases to keep the cost and size down, it would be reasonable to chose the required type of a table-top laser having just those parameters which are needed by a given application since it is clear that applications in science, industry, metrology, inspection, active and passive diagnostics, heating, surface modification, and plasma ionization are very different. On the way of further increasing the peak brightness which is the most important parameter of XRL, improvement of several parameters will be needed including:

- increasing the output energy,
- decreasing the divergence,
- shortening the pulse duration.

These are possible and will boost brightness by 3-4 orders of magnitude, elevating XRLs to match some FELs. Also, high repetition rates are achievable for laser-produced plasma XRL similar to proposed FEL or capillary XRL. This will boost average power and brightness of laser plasma XRL by orders of magnitude. Additionally, wavelength of

TABLE 1. COMET/Capillary/DESY VUV-FEL x-ray laser source parameters

Source Parameters	**COMET x-ray Laser**	**Capillary [b] x-ray laser**	**DESY VUV-FEL[c]**
Pump Energy – laser or condensor (for capillary) (J)	5 – 10	40-100	-
X-ray Laser Energy (μJ)	25	100-900	300
Photons/Shot	2×10^{12}	2×10^{14}	10^{13}
Shot Rate (Hz)	0.004	1-10	10
Wavelength (nm)	12 – 47	47, 53, 61	6
$\Delta\lambda/\lambda$	10^{-4}	10^{-4}	6×10^{-3}
Source Dimensions (μm)	25 by 100	3×10^{-2}	150
Divergence (mrad)	2.5 by 10	2-5	0.06
XRL Pulse Duration (ps)	2 – 25	700 – 1500	0.1
Peak Brightness, B [a]	1.6×10^{25}	3×10^{25}	10^{29}
Average Brightness, B [a]	1.3×10^{11}	5×10^{14}	-

[a] Units of ph. mm^{-2} $mrad^{-2}$ s^{-1} (0.1% BW) $^{-1}$; [b] parameters shown are for the 46.9nm Ne-like Ar laser; [c] Expected start operation 2005

table-top XRLs will continue to decrease which will further, and dramatically, increase the brightness. This makes table-top lasers attractive and viable alternatives to other x-ray sources except for applications that really require continuous tunability.

Recently a number of interesting applications was identified for use with future FELs which will operate at 60 Å within 3 years and will reach 1 Å within 10-12 years. The Joint Proposal for Peak Brightness Experiments on the TTF-FEL (LLNL) covers a very wide range of scientific areas from plasma physics to finite temperature condensed matter physics to biological-related imaging. Table 2 cites the main topics in this Proposal together with a brief description.

TABLE 2 Summary of the Peak Brightness Beamline Experiments

Experiment	Brief Description
Warm Dense Matter	Using the x-ray laser to uniformly warm solid density samples. Isochoric heating of a thin foil
Equation of State Measurements	Use an optical laser to heat a sample and the x-ray laser to provide a diagnostic of the bulk conditions
Femtosecond Ablation Studies	Probe the nature of the ablation process on the sub-ps time scale
Near Edge Absorption	Use an optical laser to heat a solid and the x-ray laser to probe the structural changes that occur
Trapped Strongly Coupled Plasmas	Use an EBIT / laser-cooled trap and probe highly charged strongly coupled Coulomb systems
Diagnostic Development	Develop the FEL for Thomson scattering, interferometry, and radiographic imaging
Gas-Jet Interaction	Create exotic, long-lived highly perturbed electron distribution functions in dense plasmas
Solid Interactions	Use laser directly to create extreme states of matter at high temperature and density
Plasma Spectroscopy	Use the FEL as a pump to move bound state populations and study radiation redistribution
Coulomb Explosion	Study the effects of the Coulomb Explosion process with emphasis on Biological imaging problems
Diffraction Imaging Studies	Validate imaging techniques. Perform microscopy on living systems beyond the current resolution limited by radiation damage
Optics Damage	Study structural changes and disintegration processes of solids as a function of laser intensity

All of them were inspired by the attractive properties of future FEL sources. Part of these proposed experiments require direct interaction of FEL with matter (e.g. the experiments on creating warm dense matter, plasma physics of photoionized gases, Coulomb explosions of biological samples, diffraction imaging of biological samples, optics damage and high-field effects). Others use this x-ray source just for diagnostics purposes. The proposal on optics damage experiment, for example, combines both heating and probing together. Even a short analysis of these proposals shows that most of them can be successfully realized with smaller and cheaper table-top XRLs. It should be noted that an optics damage experiment is already under way utilizing the transient Comet XRL at LLNL (see below) as well as some others like photoelectron spectroscopy studies [2]. Some experiments will require additional solid state lasers synchronized with XRL pulse of fs, ps or ns duration (as it is the case in above proposal for development of diagnostics of Thomson scattering, interferometry and radiography, equation of state measurements, femtosecond ablation studies, near-edge absorption studies, plasma spectroscopy and strongly coupled plasma studies using a laser-cooled trap). An obvious advantage of table-top XRLs is that this additional laser will be easier to implement since transient XRLs are pumped with the optical lasers and multiple synchronized beams are available.

Utilized currently mostly for scientific applications, table-top x-ray lasers are already expanding the field of traditional scientific diagnostic methods allowing to extract more detailed information, in some cases with an unprecedented accuracy. Among them are:

- **Shadowgraphy:** XRL can be used here because of high peak brightness, and in principle, can be applied as diagnostics of NIF hohlraum and other fusion experiments. In addition, this method may have exceptional sensitivity because of the exponential dependence of transparency on the plasma absorption coefficients. This has been confirmed by modeling and experiments with the argon 46.9nm capillary x-ray laser beam through an elongated plasma formed by an another capillary discharge [3]. Due to plasma inhomogeneity, the extremely sharp boundaries observed in these experiments transform into precise position of specific ion stages and are a demonstration of the mentioned sensitivity.
- **Soft x-ray imaging:** The images of plasmas were recorded in many spectral regions for numerous experiments for a wide range of conditions in capillary and laser plasmas. Of special interest was near- and far-field imaging of the capillary output and transient XRL. The experiments and numerical modeling allowed to reveal detailed data about plasma evolution, gain formation and amplification dynamics. Like with shadowgraphy, due to the same exponential dependence (this time on gain coefficient) it can be arranged as a very sensitive method for plasma diagnostics [4]. Another example of successful application of diagnostics of small variations in distribution function responsible for changes in laser radiation absorption coefficients at shorter pulse durations is demonstrated in [5].
- **X-ray spectroscopy:** This method is the most routine but when combined with XRL it can have exponential sensitivity too. It can be used to find the temperature and density of plasma column, evaluate amplification of x-ray laser etc. It can be applied to find extremely weak plasma processes like Zeeman effect [6] or isotopic hyperfine splitting in spectral lines [7] due to their influence on linewidth and hence gain.
- **Photoelectron spectroscopy:** The comparison of using transient XRL with laser plasma x-ray source shows clear advantage of XRL which provides 1-2 orders of magnitude more photons in selected spectral band and is monochromatic which is important for accuracy. The experiments are currently in progress on COMET [2].
- **Interferometry:** This promises to be the key application of x-ray lasers because it utilizes the unique property of their coherence. The coherence of the first generation of table-top x-ray lasers was sufficient to demonstrate plasma interferometry [8, 9]. Given the very high brightness of all x-ray lasers, the substantially reduced refraction and inverse bremsstrahlung absorption, and the simple straightforward relationship between electron density and index of refraction, interferometry will bring incredible precision to applications in material science, x-ray holography, metrology, dense plasma and fusion applications.

X-RAY LASER INTERFEROMETRY

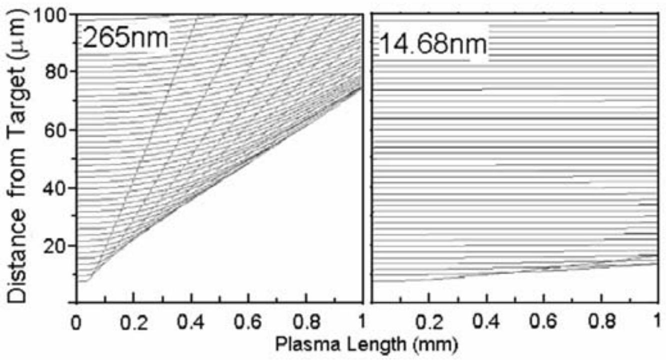


Fig. 1 RADEX ray-tracing of the probe beams of 14.68nm and 265nm wavelength through the calculated density profile. A 1mm long Al plasma is probed at 500ps after the peak of the 600ps plasma forming beam. The plasma was generated with a 6x0.04 mm line focus with an intensity of 4×10^{11} W/cm^2.

The x-ray laser interferometry, first reported on LLNL kJ-scale lasers [10], is expected to have a similar impact on the range of applications as was achieved many years ago with famous x-ray tubes. Figure 1 shows ray-tracing on a typical 1 mm long laser plasma density profile and demonstrates how challenging it is to probe plasmas of important, practical sizes [11]. This is one of the reasons, which may seem surprising, that laser plasma density profiles even at very low laser fluxes accessible for decades were not precisely characterized. Even longer plasmas, e.g. a NIF capsule could be 0.5 - 1 cm, or Z-pinches up to several cm, and in some cases an x-ray laser medium may be tens of cm long, require accurate probing to better understand the plasma conditions. In the case of [12, 13] which attempted to probe laser produced plasma using optical lasers, the refraction restricted the maximum density to around ~10^{19} cm^{-3}. As a result the density structures resembling very pronounced side lobes, which represent a general property of laser-produced plasmas, were missed by researchers (see ref. [14] for explanation). The inability to probe sufficiently high densities above a certain length with optical or UV wavelengths is clearly demonstrated by Fig. 1. This shows the detrimental ray tilt due to refraction as they propagate through the target plasma. In another calculation shown in Fig. 2 we have included both the effects of the density dependent fringe shifts and refraction-related tilting due to density gradient. The solid line is the initial density profile as was obtained from the RADEX simulations in cylindrical geometry with R_0=40 μm. The other two RADEX curves are the densities deduced from

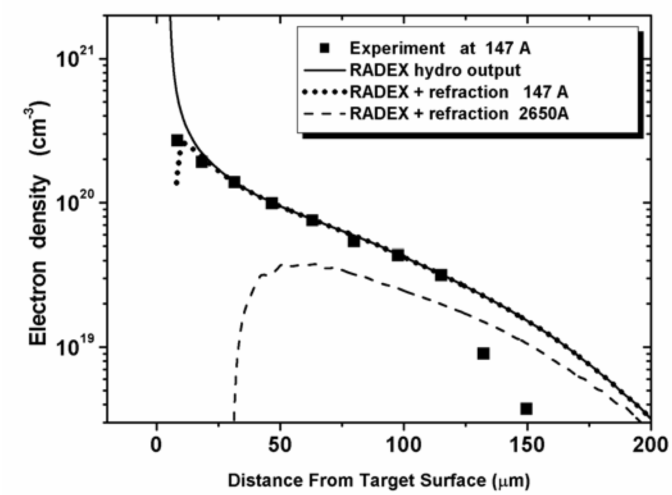


Fig. 2 RADEX calculated density profile (solid line) in comparison with experiment [squares] at 500ps after the peak of the 600ps plasma forming beam 1×10^{12} W/cm^2. Similar values were also obtained with 1.5D LASNEX. Two additional curves show reconstructed density by ray-tracing of the probe beams of 14.68nm and 265nm wavelength through 2mm long Al plasma as they would be deducted by ideal interferometer.

the simulated interference patterns based on this profile if the plasma would be probed by 147 Å or the 4ω higher harmonic (2650 Å) of a Nd-glass laser. The 'ideal' interferometer was implied in this calculation which assumes the ray path in the instrument arms is not affected if they come with different angles which is usually taken into account in real situations [9]. Fig. 2 demonstrates the advantage of XRL over UV interferometry for probing long plasmas. But at such relatively large plasma lengths even 147 Å XRL probes may give an inaccurate picture if there exist very short lateral micron-scale density gradients. As a result of very high ratio of plasma length to gradient length ~ 1000, in this particular case the probing can not come higher than approximately 3×10^{20} cm^{-3}. Larger magnifications, shorter wavelengths or smaller plasma sizes are needed to get into the regions of such small scale length at the critical surface. In all other areas where the gradients are not as severe, this method works extremely well and accurately reproduces the density profiles up to $\sim10^{22}$ cm^{-3} for a 0.1 - 0.2 cm long plasma. Higher densities $>10^{23}$ cm^{-3} almost up to XRL critical density can be probed if the gradients are negligible and the plasma length is appropriately short not to absorb the signal and to ensure a reasonable number of fringe shifts. We believe that future experiments will clearly demonstrate that with table-top XRLs we get extremely powerful and sensitive diagnostic tool with great potential.

OPTICS DAMAGE BY HIGH X-RAY FLUENCES

Opposite to numerous kinds of plasma x-ray sources, the predictable parameters of radiation sources which utilize high-energy particles allow to plan the development of such sources far in advance. During the next decade the 4th generation x-ray sources promise to provide the parameters that are far beyond the reach of current 3rd generation synchrotron light sources. It has been expected that a decade from now these sources will produce unprecedented levels of peak and average brightness of monochromatic and spontaneous x-ray radiation. With brightness and fluences of this level there will be no materials which can withstand these fluxes without destruction. As a result, one of the important application in this case is investigation of damage thresholds of x-ray optics.

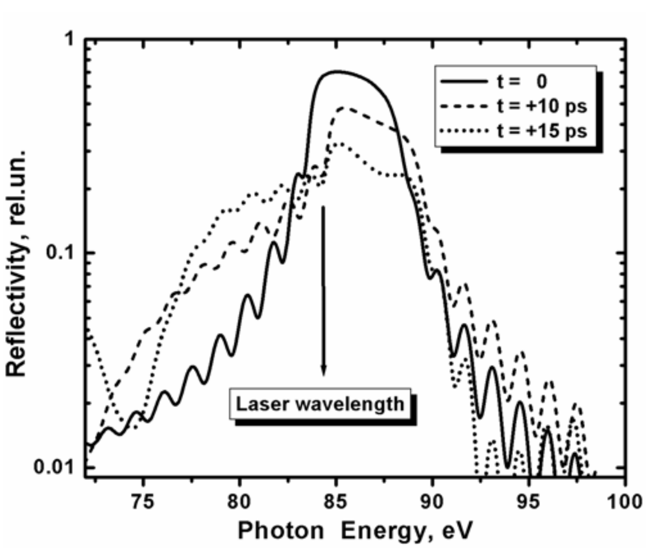


Fig. 3. Modeling of the X-ray reflectivity of a Mo/Si multilayer mirror under the incidence angle of 8 degrees (50 pairs, 30Å Mo/45Å Si on a silicon substrate), where t=0 is the beginning of the incident laser pulse: duration 5 ps at FWHM, intensity 1.7 10^{11} W/cm^2, photon energy 84.4 eV.

One of such x-ray SASE sources will be the Linac Coherent Light Source (LCLS) at Stanford while another at DESY laboratory in Hamburg, Germany is currently constructing a 60 Å source as part of the TESLA linear collider project. The BESSY laboratory at Berlin, Germany, is also designing a 12 Å SASE FEL User Facility.

To emulate optics damage effects we are using laboratory sources of optical and x-ray radiation including femtosecond solid state lasers, K-α plasma sources and x-ray lasers. The experiments with optical wavelengths of similar fluences were performed at LLNL which produced unexplainable results due to potentially non-linear interaction of radiation with matter [15] though optical wavelength interaction physics is very different from x-rays. Given the same nature and reliable values for absorption which will not leave linear regimes, and given the increased accessibility of table-top x-ray lasers the project is under development to utilize the COMET x-ray laser at LLNL. The main interest with this experiment is to emulate the interaction of 10 keV photons of future FEL x-ray sources similar to the LCLS. With the proposed design the 84.4 eV COMET XRL fits well to this goal because the damage layer caused by 10 keV radiation is defined by photoelectron stopping length, 0.5 - 1 μm, and is similar to the photo-absorption length of 84.4 eV XRL radiation for certain materials. To increase sensitivity of the method and at the same time reflectivity which in x-ray region for solid materials at normal incidence is typically very small we proposed to use multilayer mirrors as a test object. The substantial increase of sensitivity of the method will be due to resonance properties of multilayer mirrors.

RADEX and LASNEX simulations were used to predict the heating and expansion of the multilayers under the influence of radiation from the COMET XRL. The reflection coefficient was obtained as a function of photon energy, incidence angle, laser flux and time. Figure 3, shows the dynamic changes in reflectivity of a Mo/Si multilayer mirror modeled with the codes RADEX and XOP. These changes are seen on the hydrodynamics timescale when several top layer pairs will expand into the vacuum. Other physical effects, such as phase transitions, are expected to be observed which may occur with potentially different timescales (from sub-ps to ns-scales) based on their different reflectivity temporal, spectral and angular behavior.

CAPILLARY DISCHARGE STUDIES

The capillary discharge as one of variants of Z-pinches attracted attention of plasma physics researchers for almost two decades. It has been used for hot dense plasma formation and x-ray lasers [16, 17], for transportation of laser beams and XUV radiation generation in x-ray lithography [18, 19], basic Z-pinch research and some other applications. Due to its geometry, and achievable high densities and temperatures, Z-pinches represent a natural medium for x-ray lasers. Substantial experimental and theoretical efforts are now devoted to extend this kind of XRL to shorter wavelengths because of obvious benefit of 100 – 150 Å range relevant to projection EUV lithography and other practical needs.

The progress in parameters of capillary materials and electric drivers for capillary discharges allowed the achievement of 200 kA currents with 10 ns risetime. This in turn enabled to reach higher temperatures $T_e \sim 200$-400 eV, densities $N_e > 10^{20}$ cm^{-3}, and as large as 300 times density compression ratios in high-Z plasma needed for next generation of capillary discharge XRLs [17, 20]. With such temperatures and densities the collisional XRL scheme on Ni-like ions becomes feasible. The atomic numbers of elements suitable for lasing are in the range 42 - 50 which are lasing at wavelengths down

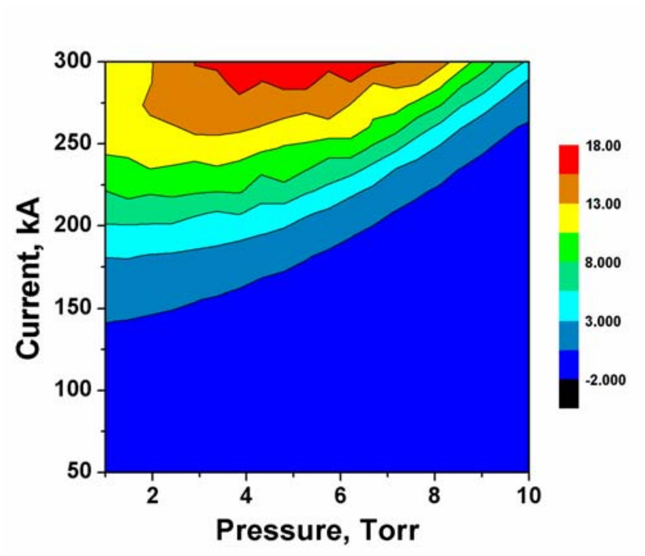
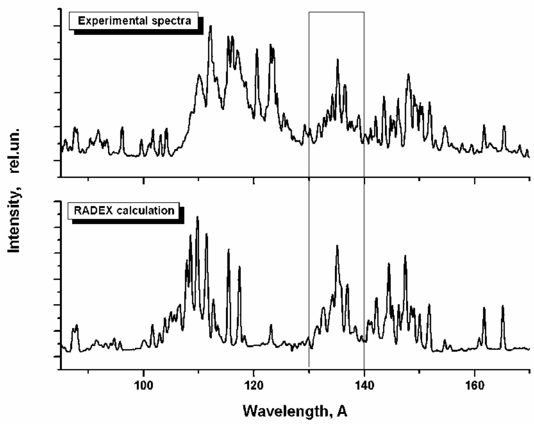


Fig. 4 Small signal gain on 4d-4p transitions in Ni-like AgXX as a function of current and pressure. Current pulse duration is set 20ns, capillary diameter is 3.3 mm.

to ~100 Å. For Ni-like ions e.g. Cd XXI, the gain is calculated to be ~1-2 cm^{-1}, which is in qualitative agreement with the current experimental data [20]. Figure 4 shows the results of numerical calculations of small signal gain for the Ni-like ion AgXX obtained with over 400 hydro/atomic kinetics runs. The numerical model, as usual, involves plasma heating, ionization, radiation transport and material ablation physics. The calculated gain is substantially larger than using Cd. We plan the experiments with the Ni-like Ag ion in the future.

Z-pinches are naturally efficient x-ray and EUV sources so that they can be used for many important applications in science and technology. In particular, the capillary discharge can appear as powerful potential candidate for emerging EUV microlithography. We will shortly describe this potentially very important application of capillary discharges. It is not a coherent or even monochromatic source like an x-ray laser but their physics and numerical models are very strongly related so that the new data and knowledge obtained in either case is equally beneficial. Hence, it is possible to consider x-ray conversion studies as a very useful side product of x-ray laser research. In fact, the RADEX code can treat the hydrodynamics, atomic kinetics and radiation transport for these two cases in almost the same way. EUVL sources must match the specific practical, technological and environmental requirements of complex processes of microchip production. Among the requirement are the achievement of efficient x-ray conversion in the specific spectral range of interest, high average power, pulse-to-pulse stability, large source lifetime etc. The extremely high spatial and temporal stability (radial position jitter of dense plasma column can be comparable to laser plasma, ~20 microns or less), relatively large temperatures achieved with small currents, simplicity and efficiency attracted the attention of researchers to develop capillary plasmas as a radiation source.

Numerous experiments with different capillary materials, currents and gas fills were performed in CREOL and Sandia National Labs [19, 21, 22]. The parameters of this discharge are somewhat intermediate between capillary XRL case and one of 300 μm microcapillary investigated previously [3] since the discharge source has been driven by much smaller (3 - 6 kA) and longer (1 - 2 μs) current pulses. We compared our simulations with the optical interferometry of capillary discharge plasma performed at CREOL and found good agreement in source size, density spatial temporal behavior. We also reproduced spectra obtained in Sandia National Labs capillary discharge source [23].



XeVIII	117A: 4p5s-g, 4p5p–g
XeIX	90A: 4d5f-g, 4d6p-g, 117A: 4d4f-g, 123A: 4p5s-4d5s 135A: 4p5s-4d5s, 4p5p-4d5p, 145A: 4d4f-g, 163A: 4d5p-g
XeX	90A: 4d5f-g 110A: 4d4f-g, 4p4d-g, 145A: 4d5p-g, 4d4f-g
XeXI	80A: 4d5f-g, 110A: 4d4f-g, 4p4d-g, 135A: 4d5p-g, 4d4f-g, 4d5f-g

Fig. 5 The experimental (top) and RADEX calculated spectra (bottom) of capillary discharge. Table3 summarizes transitions which contribute to these spectra. g here denoted ground state(s)

To describe spectra correctly, the atomic kinetics model data size for high-Z gases like Xe used in this source reach tremendous dimensions of the order of 1 GB due to the number of ion stages XeVIII - XeXI involved, the atomic levels of the order of 10^4 and spectral lines approaching 10^6. The main source of radiation in such systems is due to numerous spectral lines often many times overlapped over instrumental resolution of ~0.2 Å. The spectra obtained from 5 kA 1.4 μs diamond capillary discharge in Xe at 2 Torr in comparison with modeling spectra are shown in Fig. 5. Table 3 marks the major transitions contributing into different spectral bands. Some missing transitions in RADEX spectra around 120 Å are due to omission in the calculations of the lower Z stages Xe V - VII radiating at much lower temperatures. The calculations done with a wide range of parameters clearly support the observations that Ru-like Xe ions (Xe XI) are contributing the most into the 135 Å region of interest for microlithography. We will continue modeling this source for further optimization for lithography.

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